

**Title:** Tree height and leaf drought tolerance traits shape growth responses across droughts in a temperate broadleaf forest

**Authors:** Ian R. McGregor<sup>1,2</sup>, Ryan Helcoski<sup>1</sup>, Norbert Kunert<sup>1,3</sup>, Alan J. Tepley<sup>1,4</sup>, Erika B. Gonzalez-Akre<sup>1</sup>, Valentine Herrmann<sup>1</sup>, Joseph Zailaa<sup>1,5</sup>, Atticus E.L. Stovall<sup>1,6,7</sup>, Norman A. Bourg<sup>1</sup>, William J. McShea<sup>1</sup>, Neil Pederson<sup>8</sup>, Lawren Sack<sup>9,10</sup>, Kristina J. Anderson-Teixeira<sup>1,3\*</sup>

**Author Affiliations:**

1. Conservation Ecology Center; Smithsonian Conservation Biology Institute; National Zoological Park, Front Royal, VA 22630, USA
2. Center for Geospatial Analytics; North Carolina State University; Raleigh, NC 27607, USA
3. Center for Tropical Forest Science-Forest Global Earth Observatory; Smithsonian Tropical Research Institute; Panama, Republic of Panama
4. Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada
5. Biological Sciences Department; California State University; Los Angeles, CA 90032, USA
6. Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903, USA
7. NASA Goddard Space Flight Center; Greenbelt, MD 20771, USA
8. Harvard Forest, Petersham, MA 01366, USA
9. Department of Ecology and Evolutionary Biology; University of California, Los Angeles; Los Angeles, CA 90095, USA
10. Institute of the Environment and Sustainability; University of California, Los Angeles; Los Angeles, CA 90095, USA

\*corresponding author: teixeirak@si.edu; +1 540 635 6546

| Text   | word count                  | other                              | n              |
|--|-----------------------------|------------------------------------|----------------|
| Total word count (excluding summary, references and legends) | 6,490 ( <b>Limit 6500</b> ) | No. of figures                     | 4 (all colour) |
| Summary  | 200                         | No. of Tables                      | 3              |
| Introduction   | 1,264                       | No of Supporting Information files | 19             |
| Materials and Methods  | 2,228                       |                                    |                |
| Results  | 929                         |                                    |                |
| Discussion   | 1927                        |                                    |                |
| Acknowledgments  | 142                         |                                    |                |

## Summary

- As climate change drives increased drought in many forested regions, mechanistic understanding of the factors conferring drought tolerance in trees is increasingly important. The dendrochronological record provides a window through which we can understand how tree size and traits shape growth responses to droughts.
- We analyzed tree-ring records for twelve species in a broadleaf deciduous forest in Virginia (USA) to test hypotheses on how tree height, microenvironment characteristics, and species' traits shaped drought responses across the three strongest regional droughts over a 60-year period.
- Drought tolerance (resistance, recovery, and resilience) decreased with tree height, which was strongly correlated with exposure to higher evaporative demand and solar radiation. The potentially greater rooting volume of larger trees did not confer a resistance advantage, but marginally increased recovery and resilience, in sites with low topographic wetness index. Drought tolerance was greater among species whose leaves experienced less shrinkage upon desiccation and lost turgor (wilted) at more negative water potentials.
- The tree-ring record reveals that tree height and leaf drought tolerance traits influenced growth responses during and after significant droughts in the meteorological record. As climate change-induced droughts intensify, tall trees with drought-sensitive leaves will be most vulnerable to immediate and longer-term growth reductions.

*Key words:* annual growth; crown exposure; drought; Forest Global Earth Observatory (ForestGEO); leaf drought tolerance traits; temperate broadleaf deciduous forest; tree height; tree-ring

## Introduction

Forests play a critical global role in climate regulation (Bonan, 2008), yet there remains enormous uncertainty as to how the forest-dominated terrestrial carbon sink will respond to climate change (Friedlingstein et al., 2006). An important aspect of this uncertainty lies with physiological responses of trees to drought (Kennedy et al., 2019). In many forested regions around the world, the risk of severe drought is increasing (Trenberth et al., 2014; Dai et al., 2018), often despite increasing precipitation (Intergovernmental Panel on Climate Change, 2015; Cook et al., 2015). Droughts, intensified by climate change, have been affecting forests worldwide and are expected to continue as one of the most important drivers of forest change in the future (Allen et al., 2010, 2015; McDowell et al., 2020). Understanding forest responses to drought requires elucidation of how tree size, microenvironment, and species’ traits jointly influence individual-level drought tolerance, defined here as a tree’s ability to maintain growth during drought (resistance) and to recover to its pre-drought growth rate (resilience) (Lloret et al., 2011). Because the resistance and resilience of growth to drought are linked to trees’ probability of surviving drought (DeSoto et al., 2020; Liu et al., 2019), understanding growth responses can also help elucidate which trees are most vulnerable to drought-induced mortality. However, it has proven difficult to resolve the many factors affecting tree growth during drought and the extent to which their influence is consistent across droughts. This is because available forest census data only rarely captures extreme drought, whereas tree-ring records capture multiple droughts but typically focus on only the largest individuals of one or a few species.

Many studies have shown that within and across species, large trees tend to be more affected by drought. Greater growth reductions (*i.e.*, lower drought resistance) in larger trees were first shown on a global scale by Bennett et al. (2015), and subsequent studies have reinforced this finding (*e.g.*, Gillerot et al., 2020). Although lower recovery and resilience of larger trees have also been observed (Hacket-Pain et al., 2016; Gillerot et al., 2020), in general we have much more limited understanding of how and why these scale with tree size.

*physiological model of Trugman et al. (2018) predicts that recovery and resilience would not necessarily be lower, even in trees that will ultimately die.*

Moreover, it has yet to be resolved which of several potential underlying mechanisms most strongly shape these trends in drought response. First, tree height itself may be a primary driver. Taller trees face the biophysical challenge of lifting water greater distances against the effects of gravity and friction (McDowell et al., 2011; McDowell and Allen, 2015; Ryan et al., 2006; Couvreur et al., 2018). Vertical gradients in stem and leaf traits—including smaller and thicker leaves (higher leaf mass per area, LMA), greater resistance to hydraulic dysfunction (*i.e.*, more negative water potential at 50% loss of hydraulic conductivity, more negative P50), and lower hydraulic conductivity at greater heights (Couvreur et al., 2018; Koike et al., 2001; McDowell et al., 2011)—enable trees to become tall (Couvreur et al., 2018). Greater stem capacitance (*i.e.*, water storage capacity) of larger trees may also confer resistance to transient droughts (Phillips et al., 2003; Scholz et al., 2011). Taller trees have wider conduits in the basal portions of taller trees, both within and across species (Olson et al., 2018; Liu et al., 2019) and throughout the conductive systems of angiosperms (Zach et al., 2010; Olson et al., 2014, 2018), which help maintain constant the resistance that would otherwise increase as trees grow taller. Wider xylem conduits plausibly make large trees more vulnerable to embolism during drought (Olson et al., 2018), and traits conducive to efficient water transport may also lead to poor ability to recover from or re-route water around embolisms (Roskilly et al., 2019). **(here would be a good place to comment on resilience. “What may help the tree in competition, therefore,**

can also be a detriment to drought resilience.”)

Larger trees may also have lower drought tolerance because of microenvironmental and ecological factors. Their crowns tend to occupy more exposed canopy positions, which are associated with higher evaporative demand (Kunert et al., 2017). Subcanopy trees tend to fare better specifically due to the benefits of a buffered environment (Pretzsch et al., 2018). Counteracting the liabilities associated with tall height, large trees tend to have larger root systems (Enquist and Niklas, 2002; Hui et al., 2014), potentially mitigating some of the biophysical challenges they face by allowing greater access to water. Larger root systems—if they grant access to deeper water sources—would be particularly advantageous in drier microenvironments (e.g., hilltops, as compared to valleys and streambeds) during drought. Finally, tree size-related responses to drought can be modified by species’ traits and their distribution across size classes (Meakem et al., 2018; Liu et al., 2019). Understanding the mechanisms driving the greater relative growth reductions of larger trees during drought requires sorting out the interactive effects of height and associated exposure, root water access, and species’ traits.

Debates have also arisen regarding the traits influencing tree growth responses to drought. Studies within temperate broadleaf forests have observed ring-porous species showing higher drought tolerance than diffuse-porous species (Friedrichs et al., 2009; Elliott et al., 2015; Kannenberg et al., 2019), but this distinction does not always hold (Martin-Benito and Pederson, 2015), would not hold in the global context (Wheeler et al., 2007; Olson et al., 2020) and does not resolve differences among the many species within each category. Commonly-measured traits including wood density and leaf mass per area (*LMA*) have been linked to drought responses within some temperate deciduous forests (Abrams, 1990; Guerfel et al., 2009; Hoffmann et al., 2011; Martin-Benito and Pederson, 2015) and across forests worldwide (Greenwood et al., 2017). However, in other cases these traits could not explain drought tolerance (e.g., in a tropical rainforest; Maréchaux et al., 2019), or the direction of response was not always consistent. For instance, higher wood density has been associated with greater drought resistance at a global scale (Greenwood et al., 2017), but correlated negatively with tree performance during drought in a broadleaf deciduous forest in the southeastern United States (Hoffmann et al., 2011). Thus, the perceived influence of these traits on drought resistance may actually reflect indirect correlations with other traits that more directly drive drought responses (Hoffmann et al., 2011).

In contrast, hydraulic traits have direct physiological linkages to tree growth and mortality responses to drought. For instance, water potentials at which percent the loss of conductivity surpasses a certain threshold (e.g., P50 and P88, representing 50 and 88% loss of conductivity, respectively) and hydraulic safety margin (*i.e.*, difference between typical minimum water potentials and P50 or P88) correlate with drought performance across global forests (Anderegg et al., 2016). However, these are time-consuming to measure and therefore infeasible for predicting or modeling drought responses in highly diverse forests (*e.g.*, in the tropics). More easily-measurable leaf drought tolerance traits that have direct linkage to plant hydraulic function can explain variation in plant distribution and function (Medeiros et al., 2019). These include leaf area shrinkage upon desiccation ( $PLA_{dry}$ ; Scoffoni et al., 2014) and the leaf water potential at turgor loss point ( $\pi_{tlp}$ ), *i.e.*, the water potential at which leaf wilting occurs (Bartlett et al., 2016a; Zhu et al., 2018). Both traits correlate with hydraulic vulnerability and drought tolerance as part of unified plant hydraulic systems (Scoffoni et al., 2014; Bartlett et al., 2016a; Zhu et al., 2018; Farrell et al., 2017). The abilities of both  $PLA_{dry}$  and  $\pi_{tlp}$  to explain the drought tolerance of tree growth remains untested.

Here, we examine how tree height, microenvironment characteristics, and species’ traits collectively shape

three metrics of drought tolerance: (1) resistance, defined as the ratio of annual stem growth in a drought year to that which would be expected in the absence of drought based on previous years' growth; (2) recovery, defined the ratio of post-drought growth to growth during the drought year; and (3) resilience, defined as the ratio of post-drought to pre-drought growth (Lloret et al., 2011). We test a series of hypotheses and associated specific predictions (Table 1) based on the combination of tree-ring records from the three strongest droughts over a 60-year period (1950 - 2009), species trait measurements, and census and microenvironmental data from a large forest dynamics plot in Virginia, USA. First, we focus on how tree size, alone and in its interaction with microenvironmental gradients, influences drought tolerance. We examine the contemporary relationship between tree height and microenvironment, including growing season meteorological conditions and crown exposure. We then test whether, consistent with most forests globally, larger-diameter, taller trees tend to have lower drought tolerance in this forest, which is in a region (eastern North America) represented by only two studies in the global review of (Bennett et al., 2015). We also test for an influence of potential access to available soil water, which should be greater for larger trees in dry but not in perpetually wet microsites. Finally, we focus on the role of species' traits, testing the hypothesis that species' traits—particularly leaf drought tolerance traits—predict drought tolerance. We test predictions that drought tolerance is higher in ring-porous than semi-ring and diffuse-porous species and that it is correlated with wood density—either positively (Greenwood et al., 2017) or negatively (Hoffmann et al., 2011) and positively correlated with *LMA*. We further test predictions that species with low *PLA<sub>dry</sub>* and those whose leaves lose turgor at lower water potentials (more negative  $\pi_{tlp}$ ) have higher tolerance.

## Materials and Methods

### *Study site and microclimate*

Research was conducted at the 25.6-ha ForestGEO (Forest Global Earth Observatory) study plot at the Smithsonian Conservation Biology Institute (SCBI) in Virginia, USA (38°53'36.6"N, 78°08'43.4"W; Fig. S1) (Bourg et al., 2013; Anderson-Teixeira et al., 2015a). SCBI is located in the central Appalachian Mountains near the northern boundary of Shenandoah National Park. Elevations range from 273 to 338 m above sea level with a topographic relief of 65m (Bourg et al., 2013). Climate is humid temperate, with mean annual temperature of 12.7°C and precipitation of 1005 mm yr<sup>-1</sup> during our study period (1960-2009; source: CRU TS v.4.01; Harris et al., 2014). Dominant tree taxa within this secondary forest include *Liriodendron tulipifera*, oaks (*Quercus* spp.), and hickories (*Carya* spp.; Table 2).

### *Identifying drought years*

We identified the three largest droughts within the time period 1950-2009, defining drought (Slette et al., 2019) as events with anomalously dry peak growing season climatic conditions. Specifically, we used the metric of Palmer Drought Severity Index (PDSI) during May-August (MJJA; Table S1), which were identified by Helcoski et al. (2019) as the months of the current year to which annual tree growth was most sensitive at this site. PDSI divisional data for Northern Virginia were obtained from NOAA (<https://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp>) in December 2017. Based on this, we identified the three strongest droughts during the study period (Figs. 1, S1; Table S1).

The droughts differed in intensity and antecedent moisture conditions (Fig. S1, Table S1). The 1966 drought was preceded by two years of moderate drought during the growing season and severe to extreme drought starting the previous fall. In August 1966, *PDSI* reached its lowest monthly value (-4.82) of the three

droughts. The 1977 drought was the least intense throughout the growing season, and it was preceded by 2.5 years of near-normal conditions, making it the mildest of the three droughts. The 1999 drought was preceded by wetter than average conditions until the previous June, but *PDSI* plummeted below -3.0 in October 1998 and remained below this threshold through August 1999. Following all three droughts, *PDSI* rebounded to near-normal conditions in September or October (Fig. **S1**).

#### *Data collection and preparation*

Within or just outside the ForestGEO plot, we collected data on a suite of variables including tree heights, microenvironment characteristics, and species traits (Table 3). The SCBI ForestGEO plot was censused in 2008, 2013, and 2018 following standard ForestGEO protocols, whereby all free-standing woody stems  $\geq 1$  cm diameter at breast height (DBH) were mapped, tagged, measured at DBH, and identified to species (Condit, 1998). From these census data, we used measurements of DBH from 2008 to calculate historical DBH and data for all stems  $\geq 10$  cm to analyze functional trait composition relative to tree height (all analyses described below). Census data are available through the ForestGEO data portal ([www.forestgeo.si.edu](http://www.forestgeo.si.edu)).

We analyzed tree-ring data (xylem growth increment) from 571 trees representing the twelve dominant species (Table 2; Fig. **S2**). Selected species were those with the greatest contributions to woody aboveground net primary productivity ( $ANPP_{stem}$ ) and together comprised 97% of study plot  $ANPP_{stem}$  between 2008 and 2013 (Helcoski et al., 2019). Cores (one per tree) were collected within the ForestGEO plot at breast height (1.3m) in 2010-2011 or 2016-2017. In 2010-2011, cores were collected from randomly selected live trees of each species that had at least 30 individuals  $\geq 10$  cm DBH (Bourg et al., 2013). Annual tree mortality censuses were initiated in 2014 (Gonzalez-Akre et al., 2016), and in 2016-2017, cores were collected from all trees found to have died since the previous year's census. We note that drought was probably not a cause of mortality for these trees, as monthly May-Aug *PDSI* did not drop below -1.75 in these years or the three years prior (2013-2017), and that trees cored dead displayed similar climate sensitivity to trees cored live (Helcoski et al., 2019). Lagged drought-induced mortality would be unlikely, given that the trees analyzed here lived at least 17-18 years past the most recent major drought (1999), whereas the meta-analysis of Trugman et al. (2018) indicates that  $>10$ -year lags in drought-attributed mortality are rare. Cores were sanded, measured, and crossdated using standard procedures, as detailed in (Helcoski et al., 2019). The resulting chronologies (Fig. **1a**) were published in Zenodo (Gonzalez-Akre et al., 2019).

For each cored tree, we combined tree-ring records and allometric equations of bark thickness to reconstruct DBH for the years 1950-2009. Prior *DBH* was estimated using the following equation:

$$DBH_Y = DBH_{2008} - 2 * \left[ r_{bark,2008} - r_{bark,Y} + \sum_{year=Y}^{2008} r_{ring,Y} \right]$$

Here,  $Y$  denotes the year of interest,  $r_{ring}$  denotes ring width derived from cores, and  $r_{bark}$  denotes bark thickness, which was estimated from species-specific allometries based on the bark thickness data from the site (Table S2; Anderson-Teixeira et al., 2015b).

Tree heights ( $H$ ) were measured by several researchers for a variety of purposes between 2012 and 2019 ( $n=1,518$  trees). Methods included direct measurements using a collapsible measurement rod on small trees (NEON, 2018) or a tape measure on recently fallen trees (this study); geometric calculations using clinometer and tape measure (Stovall et al., 2018a) or digital rangefinders (Anderson-Teixeira et al., 2015b; NEON,

203 2018); and ground-based LiDAR (Stovall et al., 2018b). Rangefinders used either the tangent method  
 204 (Impulse 200LR, TruPulse 360R) or the sine method (Nikon ForestryPro) for calculating heights. Both  
 205 methods are associated with some error (Larjavaara and Muller-Landau, 2013), but in this instance there was  
 206 no clear advantage of one or the other. Measurements from the National Ecological Observatory Network  
 207 (NEON) were collected near the ForestGEO plot following standard NEON protocol, whereby vegetation of  
 208 short stature was measured with a collapsible measurement rod, and taller trees with a rangefinder (NEON,  
 209 2018). Species-specific height allometries were developed using log-log regression ( $\ln[H] \sim \ln[DBH]$ ; Table  
 210 S3). For species with insufficient height data to create reliable species-specific allometries (n=2, JUNI and  
 211 FRAM), heights were calculated from an equation developed by combining the height measurements across  
 212 all species. We then used these allometries to estimate  $H$  for each drought year,  $Y$ , based on reconstructed  
 213  $DBH_Y$  (Fig. S3).

214 To characterize how environmental conditions vary with height, data were obtained from the NEON tower  
 215 located <1km from the study area via the neonUtilities package (Lunch et al., 2020). We used wind speed,  
 216 relative humidity, and air temperature data, all measured over a vertical profile spanning heights from 7.2 m  
 217 to above the top of the tree canopy (31.0 or 51.8m, depending on censor), for the years 2016-2018 (NEON,  
 218 2018). After filtering for missing and outlier values, we determined the daily minima and maxima, which we  
 219 then aggregated at the monthly scale.

220 Crown position—a categorical variable classifying trees based on exposure to sunlight—was recorded for all  
 221 cored trees that remained standing during the growing season of 2018 following the protocol of Jennings et al.  
 222 (1999). Trees were classified as follows: *dominant* trees were defined as those with crowns above the general  
 223 level of the canopy, *co-dominant* trees as those with crowns within the the canopy; *intermediate* trees as  
 224 those with crowns below the canopy level, but illuminated from above; and *suppressed* as those below the  
 225 canopy and receiving minimal direct illumination from above.

226 Topographic wetness index (TWI), used here as a metric of long-term mean moisture availability, was  
 227 calculated using the dynatopmodel package in R (Fig. S2) (Metcalfe et al., 2018). Originally developed by  
 228 Beven and Kirkby (1979), TWI was part of a hydrological run-off model and has since been used for a  
 229 number of purposes in hydrology and ecology (Sørensen et al., 2006). TWI calculation depends on an input  
 230 of a digital elevation model (DEM; ~3.7 m resolution from the elevatr package (Hollister, 2018)), and from  
 231 this yields a quantitative assessment defined by how “wet” an area is, based on areas where run-off is more  
 232 likely. From our observations in the plot, TWI performed better at categorizing wet areas than the Euclidean  
 233 distance from the stream.

234 Species’ trait data were collected in August 2018 (Tables 2-3; Fig. S4). We sampled small, sun-exposed  
 235 branches up to eight meters above the ground from three individuals of each species in and around the  
 236 ForestGEO plot. Sampled branches were re-cut under water at least two nodes above the original cut and  
 237 re-hydrated overnight in covered buckets under opaque plastic bags before measurements were taken.  
 238 Rehydrated leaves taken towards the apical end of the branch (n=3 per individual: small, medium, and  
 239 large) were scanned, weighed, dried at 60° C for  $\geq 48$  hours, and then re-scanned and weighed. Leaf area  
 240 was calculated from scanned images using the LeafArea R package (Katabuchi, 2019).  $LMA$  was calculated  
 241 as the ratio of leaf dry mass to fresh area.  $PLA_{dry}$  was calculated as the percent loss of area between fresh  
 242 and dry leaves. Wood density was calculated for ~1cm diameter stem samples (bark and pith removed) as  
 243 the ratio of dry weight to fresh volume, which was estimated using Archimedes’ displacement. We used the  
 244 rapid determination method of Bartlett et al. (2012) to estimate osmotic potential at turgor loss point ( $\pi_{tlp}$ ).

Briefly, two 4 mm diameter leaf discs were cut from each leaf, tightly wrapped in foil, submerged in liquid nitrogen, perforated 10-15 times with a dissection needle, and then measured using a vapor pressure osmometer (VAPRO 5520, Wescor, Logan, UT, USA). Osmotic potential ( $\pi_{osm}$ ) given by the osmometer was used to estimate ( $\pi_{tlp}$ ) using the equation  $\pi_{tlp} = 0.832\pi_{osm}^{-0.631}$  (Bartlett et al., 2012).

### Statistical Analysis

For each drought year, we calculated metrics of drought resistance ( $Rt$ ), recovery ( $Rc$ ), and resilience ( $Rs$ ), following Lloret et al. (2011) (Table 3). We defined  $Rt$  as the ratio of basal area increment ( $BAI$ ; *i.e.*, change in cross-sectional area) during the drought year to the mean  $BAI$  over the five years preceding the drought.  $Rc$  was defined as the ratio of mean  $BAI$  over the five years following the drought to  $BAI$  of the drought year.  $Rs$  was defined as the ratio of mean  $BAI$  over the five years following the drought to that of the five years preceding the drought. Thus, for all metrics, values  $<1$  and  $>1$  indicate growth reductions and increases, respectively.

Because these metric could potentially be biased by directional pre-drought growth trends, we also tried an intervention time series analysis (ARIMA, Hyndman et al., 2020) that predicted mean drought-year growth based on trends over the preceding ten years and used this value in place of the five-year mean in calculations of resistance ( $Rt_{ARIMA}$  = observed  $BAI$  / predicted  $BAI$ ).  $Rt$  and  $Rt_{ARIMA}$  were strongly correlated (Fig. S5), and showed similar responses to the independent variables of interest (cf. Tables S4-S5, S8-S9). Visual review of the individual tree-ring sequences with the largest discrepancies between these metrics revealed that  $Rt$  was less prone to unreasonable estimates than  $Rt_{ARIMA}$ . We therefore determined that use of 5-year means, as described above, were more appropriate metrics than those based on ARIMA projections.

Analyses focused on testing the predictions presented in Table 1 with  $Rt$  (or  $Rt_{ARIMA}$ ),  $Rc$ , or  $Rs$  as the response variable. Models were run for all drought years combined and for each drought year individually. The general statistical model for hypothesis testing was a mixed effects model, implemented in the lme4 package in R (Bates et al., 2019). In the multi-year model, we included a random effect of tree nested within species and a fixed effect of drought year to represent the combined effects of differences in drought characteristics. Individual year models included a random effect of species. All models included fixed effects of independent variables of interest (Tables 1,3) as specified below. All variables across all best models had variance inflation factors  $<1.2$  ( $1 \pm 0.019$ ). We used Akaike information criterion with correction for small sample sizes (AICc; see Brewer et al., 2016) to assess model selection, and conditional/marginal R-squared to assess model fit as implemented in the AICcmodavg package in R (Mazerolle and portions of code contributed by Dan Linden., 2019). Individual model terms were considered significant when their addition to a model improved fit at  $\Delta AICc \geq 2.0$ , where  $\Delta AICc$  is the difference in AICc between models with and without the trait.

To avoid over-fitting models with five species traits (Table 3) across only 12 species, we did not include all traits as fixed effects in a single linear mixed model, but rather conducted individual tests of each species trait to determine the relative importance and appropriateness for inclusion in the main model. These tests followed the model structure specified above, then added  $\ln[H]$  and  $\ln[TWI]$  to create a base model against which we tested traits. Trait variables were considered appropriate for inclusion in the main model if their addition to the base model significantly improved fit for at least one metric of drought tolerance ( $Rt$ ,  $Rc$ , or  $Rs$ ; Tables S4,S6-S7). While we tested xylem porosity as a predictor (Table 1), we did not consider it appropriate for inclusion in the main model because of highly uneven distribution of species across categories



(Table 2) and opposite drought responses of the only two diffuse-porous species (detailed below).

We then determined the top full models for predicting each dependent variable. To do so, we compared models with all possible combinations of candidate variables, including  $\ln[H]*\ln[TWI]$  and species traits as specified above. We identified the full set of models within  $\Delta AICc=2$  of the best model (that with lowest AICc). When a variable appeared in all of these models and the sign of the coefficient was consistent across models, we viewed this as support for the acceptance/rejection of the associated prediction (Table 1). If the variable appeared in some but not all of these models, and its sign was consistent across models, we considered this partial support/rejection.

All analysis beyond basic data collection was performed using R version 3.6.2 (R Core Team, 2019). Other R-packages used in analyses are listed in the Supplementary Information (Appendix S1). All data, code, and results are available through the SCBI-ForestGEO organization on GitHub (<https://github.com/SCBI-ForestGEO>: SCBI-ForestGEO-Data and McGregor\_climate-sensitivity-variation repositories), with static versions corresponding to data and analyses presented here archived in Zenodo (DOIs: 10.5281/zenodo.3604993 and [TBD], respectively).

## Results

### *Tree height and microenvironment*

In the years for which we have vertical profiles in climate data (2016-2018), taller trees—or those in dominant crown positions—were generally exposed to higher evaporative demand during the peak growing season months (May-August; Fig. 2). Specifically, maximum daily wind speeds were significantly higher above the top of the canopy (40-50m) than within and below (10-30m) (Fig. 2a). Relative humidity was also somewhat lower during June-August, ranging from ~50-80% above the canopy and ~60-90% in the understory (Fig. 2b). Air temperature did not vary consistently across the vertical profile (Fig. 2c).

Crown position varied as expected with height (dominant > co-dominant > intermediate > suppressed), but with substantial variation (Fig. 2d). There were significant differences in height across all crown position classes (Fig. 2d). A comparison test between height and crown position data from the most recent ForestGEO census (2018) revealed a correlation of 0.73.

### *Community-level drought responses*

At the community level, cored trees showed substantial growth reductions in all three droughts, with a mean  $Rt$  of 0.86 in 1966 and 1999, and 0.84 in 1977 (Fig. 1b). Across the entire study period (1950-2009), the focal drought years were the three years with the largest fraction of trees exhibiting  $Rt \leq 0.7$ . Specifically, in each drought, roughly 30% of the cored trees had growth reductions of  $\geq 30\%$  ( $Rt \leq 0.7$ ): 29% in 1966, 32% in 1977, and 27% in 1999. However, some individuals exhibited increased growth, *i.e.*,  $Rt > 1.0$ : 26% of trees in 1966, 22% in 1977, and 26% in 1999. Recovery was generally strong, with  $Rc$  averaging ## in 1966, ## in 1977, and ## in 1999 (Fig. S6), and  $Rs$  averaging ## in 1966, ## in 1977, and ## in 1999 (Fig. 1c).

In the context of the multivariate model,  $Rt$  did not vary across drought years. That is, drought year as a variable did not appear in any of the top models – *i.e.*, models that were statistically indistinguishable ( $\Delta AICc < 2$ ) from the best model (see footnotes on Tables S8-S9). In contrast, both  $Rc$  and  $Rs$  varied across years, being highest in all of the top models (Tables S10-S11), in which both were highest in 1966, intermediate in 1977, and lowest in 1999.

### Tree height, microenvironment, and drought tolerance

Taller trees (based on  $H$  in the drought year) showed stronger growth reductions during drought (i.e., lower  $Rt$ ) and less resilience following drought (i.e., lower  $Rc$  and  $Rs$ ; Table 1; Fig. 4). Specifically, for  $Rt$ ,  $\ln[H]$  appeared, with negative coefficient, in the best model ( $\Delta AICc=0$ ) and all top models when evaluating the three drought years together (Tables S8-S9). The same held true for 1966 individually, but there was no significant effect of  $\ln[H]$  for 1977 or 1999 individually. For  $Rc$ ,  $\ln[H]$  appeared, with negative coefficient, in the best model without a  $\ln[H] * \ln[TWI]$  interaction, for the three drought years together and for 1977, but not for 1966 or 1999. For  $Rs$ , again considering the best models without a  $\ln[H] * \ln[TWI]$  interaction, there was a negative effect of  $\ln[H]$  for the three drought years together and for 1966 and 1977, and a non-significant negative trend in 1999.

**RESUME HERE**  $Rt$  had a significantly negative response to  $\ln[TWI]$  across all drought years combined (Fig. 4, Table S8-S9). The effect was also significant for 1977 and 1999 individually (Fig. 4, Table S8).

When  $Rt_{ARIMA}$  was used as the response variable, the effect was significant in 1977, and included in some of the top models in 1966 and 1999 (Table S9). This negates the idea that trees in moist microsites would be less affected by drought. Nevertheless, we tested for a  $\ln[H] * \ln[TWI]$  interaction, a negative sign of which could indicate that smaller trees (presumably with smaller rooting volume) are more susceptible to drought in drier microenvironments with a deeper water table. This hypothesis was rejected, as the  $\ln[H] * \ln[TWI]$  interaction was never significant, and had a positive sign in any top models in which it appeared (Tables 1, S8-S9). This term did appear with a positive coefficient in the best  $Rt_{ARIMA}$  model for all years combined (Table S9), indicating that the negative effect of height on  $Rt$  was significantly stronger in wetter microhabitats.

### Species' traits and drought tolerance

Species, as a factor in ANOVA, had significant influence ( $p < 0.05$ ) on all traits (wood density,  $LMA$ ,  $PLA_{dry}$ , and  $\pi_{tlp}$ ), with more significant pairwise differences for wood density and  $PLA_{dry}$  than for  $LMA$  and  $\pi_{tlp}$  (Table 2, Fig. S4 as characterized by the agricolae package de Mendiburu (2020)). Drought tolerance also varied across species, overall and in each drought year (Figs. 3, S7). Significant differences in  $Rt$  across species were most pronounced in 1966 with a total of seven distinct groupings, while 1977 had four and 1999 had two. Averaged across all droughts,  $Rt$  was lowest in *Liriodendron tulipifera* (mean  $Rt = 0.66$ ) and highest in *Fagus grandifolia* (mean  $Rt = 0.99$ ).

Wood density,  $LMA$ , and xylem porosity were all poor predictors of  $Rt$  (Tables 1, S4-S5). Wood density and  $LMA$  were never significantly associated with  $Rt$  in the single-variable tests and were therefore excluded from the full models. Xylem porosity was also excluded from the full models, as it had no significant influence for all droughts combined and had contrasting effects in the individual droughts: whereas ring-porous species had higher  $Rt$  than diffuse- and semi-ring-porous species in the 1966 and 1999 droughts, they had lower  $Rt$  in 1977 (Table S4). It is noteworthy that the two diffuse-porous species in our study, *Liriodendron tulipifera* and *Fagus grandifolia*, were at opposite ends of the  $Rt$  spectrum (Fig. 3), further refuting the idea that xylem porosity is a useful predictor of  $Rt$  in the context of this study.

In contrast,  $PLA_{dry}$ , and  $\pi_{tlp}$  were both negatively correlated to drought resistance and resilience (Fig. 4; Tables 1, S4-S11).  $PLA_{dry}$  had a significant influence, with negative coefficient, in full models for the three droughts combined and for the 1966 drought individually (Fig. 4; Tables S8-S9). For 1977 and 1999, it was included with a negative coefficient in some of the top models (Tables S8-S9).  $\pi_{tlp}$  was included with a

negative coefficient in the best model for both all droughts combined and for the 1977 drought individually (Fig. 4; Table S8), although its influence was not significant at  $\Delta AICc < 2$ . It was also included in some of the top models for 1999 (Tables S8-S9).

## Discussion

Tree height, microenvironment, and leaf drought tolerance traits shaped tree growth responses across three droughts at our study site (Table 1, Fig. 4). The greater susceptibility of larger trees to drought, similar to forests worldwide (Bennett et al., 2015), was driven primarily by their height (Stovall et al., 2019). Taller height was likely a liability in itself, and was also associated with greater exposure to conditions that would promote water loss and heat damage during drought (Fig. 2). There was no evidence that greater availability of, or access to, soil water availability increased drought resistance; in contrast, trees in wetter topographic positions had lower  $Rt$  (Zuleta et al., 2017; Stovall et al., 2019), and the larger potential rooting volume of large trees provided no advantage in the drier microenvironments. The negative effect of height on  $Rt$  held after accounting for species' traits, which is consistent with recent work finding height had a stronger influence on mortality risk than forest type during drought (Stovall et al., 2020). Drought tolerance was not consistently linked to species'  $LMA$ , wood density, or xylem type (ring- vs. diffuse porous), but was negatively correlated with leaf drought tolerance traits ( $PLA_{dry}$ ,  $\pi_{tlp}$ ). This is the first study to our knowledge linking  $PLA_{dry}$  and  $\pi_{tlp}$  to growth reduction during drought. The directions of these responses were consistent across droughts (Table S8), supporting the premise that they were driven by fundamental physiological mechanisms. However, the strengths of each predictor varied across droughts (Fig. 4; Tables S8-S9), indicating that drought characteristics interact with tree size, microenvironment, and traits to shape which individuals are most affected. These findings advance our knowledge of the factors that make trees vulnerable to stem growth declines during drought and, by extension, likely make them more vulnerable to mortality (Sapes et al., 2019).

The droughts considered here were of a magnitude that has occurred with an average frequency of approximately once every 10-15 years (Fig. 1a, Helcoski et al., 2019) and had substantial but not devastating impacts on tree growth (Figs. 1b). These droughts were classified as severe ( $PDSI < -3.0$ ; 1977) or extreme ( $PDSI < -4.0$ ; 1966, 1999) at our site and have been linked to tree mortality in the eastern United States (Druckenbrod et al., 2019). However, extreme, multiannual droughts such as the so-called "megadroughts" of this type that have triggered massive tree die-off in other regions (e.g., Allen et al., 2010; Stovall et al., 2019) have not occurred in the Eastern United States within the past several decades (Clark et al., 2016). Of the droughts considered here, the 1966 drought, which was preceded by two years of dry conditions (Fig. S1), severely stressed a larger portion of trees (Fig. 1b). The tendency for large trees to have lowest resistance was most pronounced in this drought, consistent with other findings that this physiological response increases with drought severity (Bennett et al., 2015; Stovall et al., 2019). Across all three droughts, the majority of trees experienced reduced growth, but a substantial portion (e.g., short understory trees, species with drought resistant traits; Fig. 4) had increased growth (Fig. 1b), consistent with prior observations that smaller trees can exhibit increased growth rates during drought (Bennett et al., 2015). It is likely because of the moderate impact of these droughts, along with other factors influencing tree growth (e.g., stand dynamics), that our best models characterize only a modest amount of variation in  $Rt$ : 11-12% for all droughts combined, and 18-25% for each individual drought (Table S8).

Consistent with studies in other forests worldwide (Bennett et al., 2015), taller trees in this forest exhibited

lower drought resistance—and also recovery and resilience. Mechanistically, this is consistent with, and reinforces, previous findings that it is impossible for trees to efficiently transport water to great heights and simultaneously maintain strong resistance and resilience to drought-induced embolism (Olson et al., 2018; Couvreur et al., 2018; Roskilly et al., 2019). Taller trees also face dramatically different microenvironments (Fig. 2). They are exposed to higher wind speeds and lower humidity (Fig. 2a-b), resulting in higher evaporative demand. Unlike other temperate forests where modestly cooler understory conditions have been documented (Zellweger et al., 2019), particularly under drier conditions (Davis et al., 2019), we observed no significant variation in air temperatures across the vertical profile (Fig. 2c). More critically for tree physiology, leaf temperatures can become significantly elevated over air temperature under conditions of high solar radiation and low stomatal conductance (Campbell and Norman, 1998; Rey-Sánchez et al., 2016). Under drought, when air temperatures tend to be warmer, direct solar radiation tends to be higher (because of less cloud cover), and less water is available for evaporative cooling of the leaves, trees with sun-exposed crowns may not be able to simultaneously maintain leaf temperatures below damaging extremes and avoid drought-induced embolism. Indeed, previous studies have shown lower drought resistance in more exposed trees (Liu and Muller, 1993; Suarez et al., 2004; Scharnweber et al., 2019). Unfortunately, collinearity between height and crown exposure in this study (Fig. 2d) makes it impossible to confidently partition causality. Additional research comparing drought responses of early successional and mature forest stands, along with short and tall isolated trees, would be valuable for more clearly disentangling the roles of tree height and crown exposure.

Belowground, taller trees would tend to have larger root systems (Enquist and Niklas, 2002; Hui et al., 2014), but this does not necessarily imply that they have greater access to or reliance on deep soil-water resources that may be critical during drought. While tree size can correlate with the depth of water extraction (Brum et al., 2019), the linkage is not consistent. Shorter trees can vary broadly in the depth of water uptake (Stahl et al., 2013), and larger trees may allocate more to abundant shallow roots that are beneficial for taking up water from rainstorms (Meinzer et al., 1999). Moreover, reliance on deep soil-water resources can actually prove a liability during severe and prolonged drought, as these can experience more intense water scarcity relative to non-drought conditions (Chitra-Tarak et al., 2018). In any case, the potentially greater access to water did not override the disadvantage conferred by height—and, in fact, greater moisture access in non-drought years (here, higher TWI) appears to make trees more sensitive to drought (Zuleta et al., 2017; Stovall et al., 2019). This may be because moister habitats would tend to support species and individuals with more mesophytic traits (Bartlett et al., 2016b; Mencuccini, 2003; Medeiros et al., 2019), potentially growing to greater heights [e.g., Detto et al. (2013)], and these are then more vulnerable when drought hits. The observed height-sensitivity of *Rt*, together with the lack of conferred advantage to large stature in drier topographic positions, agrees with the concept that physiological limitations to transpiration under drought shift from soil water availability to the plant-atmosphere interface as forests age (Bretfeld et al., 2018), such that tall, dominant trees are the most sensitive in mature forests. Again, additional research comparing drought responses across forests with different tree heights and water availability would be valuable for disentangling the relative importance of above- and belowground mechanisms across trees of different size.

The development of tree-ring chronologies for the twelve most dominant tree species at our site (Helcoski et al., 2019; Bourg et al., 2013) gave us the sample size to compare historical drought responses across species (Fig. 3) and associated traits at a single site (see also Elliott et al., 2015). Our study reinforced current understanding (see Introduction) that wood density and *LMA* are not reliably linked to drought

resistance (Table 1). Contrary to several previous studies in temperate deciduous forests (Friedrichs et al., 2009; Elliott et al., 2015; Kannenberg et al., 2019), we did not find an association between xylem porosity and drought resistance, as the two diffuse-porous species, *Liriodendron tulipifera* and *Fagus grandifolia*, were at opposite ends of the  $Rt$  spectrum (Fig. 3). While the low  $Rt$  of *L. tulipifera* is consistent with other studies (Elliott et al., 2015), the high  $Rt$  of *F. grandifolia* contrasts with studies identifying diffuse porous species in general (Elliott et al., 2015; Kannenberg et al., 2019), and the genus *Fagus* in particular (Friedrichs et al., 2009), as drought sensitive. There are two potential explanations for this discrepancy. First, other traits can and do override the influence of xylem porosity on drought resistance. Ring-porous species are restricted mainly to temperate deciduous forests, while highly drought-tolerant diffuse-porous species exist in other biomes (Wheeler et al., 2007). *Fagus grandifolia* had intermediate  $\pi_{tlp}$  and low  $PLA_{dry}$  (Fig. S4), which would have contributed to its drought resistance (Fig. 4; see discussion below). A second explanation of why *F. grandifolia* trees at this particular site had higher  $Rt$  is that the sampled individuals, reflective of the population within the plot, are generally shorter and in less-dominant canopy positions compared to most other species (Fig. S4). The species, which is highly shade-tolerant, also has deep crowns (Anderson-Teixeira et al., 2015b), implying that a lower proportion of leaves would be affected by harsher microclimatic conditions at the top of the canopy under drought (Fig. 2). Thus, the high  $Rt$  of the sampled *F. grandifolia* population can be explained by a combination of fairly drought-resistant leaf traits, shorter stature, and a buffered microenvironment.

Concerted measurement of tree-rings and leaf drought tolerance traits of emerging importance (Scoffoni et al., 2014; Bartlett et al., 2016a; Medeiros et al., 2019) allowed novel insights into the role of drought tolerance traits in shaping drought response. The finding that  $PLA_{dry}$  and  $\pi_{tlp}$  can be useful for predicting drought responses of tree growth (Fig. 4; Table 1) is both novel and consistent with previous studies linking these traits to habitat and drought tolerance. Previous studies have demonstrated that  $\pi_{tlp}$  and  $PLA_{dry}$  are physiologically meaningful traits linked to species distribution along moisture gradients (Maréchaux et al., 2015; Fletcher et al., 2018; Medeiros et al., 2019; Simeone et al., 2019; Rosas et al., 2019; Zhu et al., 2018), and our findings indicate that these traits also influence drought responses. Furthermore, the observed linkage of  $\pi_{tlp}$  to  $Rt$  in this forest aligns with observations in the Amazon that  $\pi_{tlp}$  is higher in drought-intolerant than drought-tolerant plant functional type. Further, it adds support to the idea that this trait is useful for categorizing and representing species' drought responses in models (Powell et al., 2017). Because both  $PLA_{dry}$  and  $\pi_{tlp}$  can be measured relatively easily (Bartlett et al., 2012; Scoffoni et al., 2014), they hold promise for predicting drought growth responses across diverse forests. The importance of predicting drought responses from species traits increases with tree species diversity; whereas it is feasible to study drought responses for all dominant species in most boreal and temperate forests (e.g., this study), this becomes difficult to impossible for species that do not form annual rings, and for diverse tropical forests. Although progress is being made for the tropics (Schöngart et al., 2017), a full linkage of drought tolerance traits to drought responses would be invaluable for forecasting how little-known species and whole forests will respond to future droughts (Christoffersen et al., 2016; Powell et al., 2017).

As climate change drives increasing drought in many of the world's forests (Trenberth et al., 2014; Intergovernmental Panel on Climate Change, 2015), the fate of forests and their climate feedbacks will be shaped by the biophysical and physiological drivers observed here. Our results show that taller, more exposed trees and species with less drought-tolerant leaf traits will be most affected in terms of growth during the drought year. Survival is linked to resistance and resilience [CHECK REFS] (DeSoto et al.,

2020; Gessler et al., 2020), implying it may be influenced by the same factors. Indeed, while the influence of  $PLA_{dry}$  and  $\pi_{tlp}$  on drought survival remains to be tested, taller trees have lower survival (Bennett et al., 2015; Stovall et al., 2019). As climate change-driven droughts affect forests worldwide, there is likely to be a shift from mature forests with tall, buffering trees to forests with a shorter overall stature (McDowell et al., 2020). At this point, species whose drought tolerance relies in part on existence within a buffered microenvironment (e.g., *F. grandifolia*) could in turn become more susceptible. Here, the relative importance of tree height *per se* versus crown exposure becomes crucial, shaping whether the dominant trees of shorter canopies are significantly more drought tolerant because of their shorter stature, or whether high exposure makes them as vulnerable as the taller trees of the former canopy. Studies disentangling the influence of height and exposure on drought tolerance will be critical to answering this question. Ultimately, distributions of tree heights and drought tolerance traits across broad moisture gradients suggest that forests exposed to more drought will shift towards shorter stature and be dominated by species with more drought-tolerant traits (Liu et al., 2019; Bartlett et al., 2016a; Zhu et al., 2018). Our study helps to elucidate the mechanisms behind these patterns, opening the door for more accurate forecasting of forest responses to future drought.

## Acknowledgements

We especially thank the numerous researchers who helped to collect the data used here, in particular Jennifer C. McGarvey, Jonathan R. Thompson, and Victoria Meakem for original collection and processing of cores. Thanks also to Camila D. Medeiros for guidance on leaf drought tolerance and functional trait measurements, Edward Brzostek’s lab for collaboration on leaf sampling, and Maya Prestipino for data collection. This manuscript was improved based on helpful reviews by Mark Olson and three anonymous reviewers. Funding for the establishment of the SCBI ForestGEO Large Forest Dynamics Plot was provided by the Smithsonian-led Forest Global Earth Observatory (ForestGEO), the Smithsonian Institution, and the HSBC Climate Partnership. This study was funded by ForestGEO, a Virginia Native Plant Society grant to KAT and AJT, and support from the Harvard Forest and National Science Foundation which supports the PalEON project (NSF EF-1241930) for NP.

## Author Contribution

KAT, IM, and AJT designed the research. Tree-ring chronologies were developed by RH under guidance of AJT and NP. Trait data were collected by IM, JZ under guidance of NK and LS. Other plot data were collected by IM, AS, EGA, and NB under guidance of EGA and WM. Data analyses were performed by IM under guidance of KAT and VH. KAT and IM interpreted the results. IM and KAT wrote the first draft of manuscript, and all authors contributed to revisions.

## Supplementary Information

**NEED TO UPDATE !!\*\*** Table S1. Monthly Palmer Drought Severity Index (PDSI), and its rank among all years between 1950 and 2009 (driest=1), for focal droughts.

Table S2. Species-specific bark thickness regression equations.

Table S3. Species-specific height regression equations.

Table S4. Individual tests of species traits as drivers of drought resistance, where  $Rt$  is used as the response variable.

Table S5. Individual tests of species traits as drivers of drought resistance, where  $Rt_{ARIMA}$  is used as the response variable.

Table S6. Summary of top full models for each drought instance, where  $Rt$  is used as the response variable.

Table S7. Summary of top models for each drought instance, where  $Rt_{ARIMA}$  is used as the response variable.

Figure S1. Time series of Palmer Drought Severity Index (PDSI) for the 2.5 years prior to each focal drought

Figure S2. Map of ForestGEO plot showing topographic wetness index and location of cored trees

Figure S3. Distribution of reconstructed tree heights across drought years.

Figure S4. Distribution of independent variables by species.

Figure S5. Comparison of  $Rt$  and  $Rt_{ARIMA}$  results, with residuals, for each drought scenario

Figure S6. Visualization of best model, with data, for all droughts combined.

Appendix S1. Further Package Citations

## References

- Abrams, M. D. (1990). Adaptations and responses to drought in *Quercus* species of North America. *Tree Physiology*, 7(1-2-3-4):227–238.
- Allen, C. D., Breshears, D. D., and McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, 6(8):art129.
- Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H. T., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A., and Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259(4):660–684.
- Anderegg, W. R. L., Klein, T., Bartlett, M., Sack, L., Pellegrini, A. F. A., Choat, B., and Jansen, S. (2016). Meta-analysis reveals that hydraulic traits explain cross-species patterns of drought-induced tree mortality across the globe. *Proceedings of the National Academy of Sciences*, 113(18):5024–5029.
- Anderson-Teixeira, K. J., Davies, S. J., Bennett, A. C., Gonzalez-Akre, E. B., Muller-Landau, H. C., Wright, S. J., Salim, K. A., Zambrano, A. M. A., Alonso, A., Baltzer, J. L., Basset, Y., Bourg, N. A., Broadbent, E. N., Brockelman, W. Y., Bunyavejchewin, S., Burslem, D. F. R. P., Butt, N., Cao, M., Cardenas, D., Chuyong, G. B., Clay, K., Cordell, S., Dattaraja, H. S., Deng, X., Detto, M., Du, X., Duque, A., Erikson, D. L., Ewango, C. E. N., Fischer, G. A., Fletcher, C., Foster, R. B., Giardina, C. P., Gilbert, G. S., Gunatilleke, N., Gunatilleke, S., Hao, Z., Hargrove, W. W., Hart, T. B., Hau, B. C. H., He, F., Hoffman, F. M., Howe, R. W., Hubbell, S. P., Inman-Narahari, F. M., Jansen, P. A., Jiang, M., Johnson, D. J., Kanzaki, M., Kassim, A. R., Kenfack, D., Kibet, S., Kinnaird, M. F., Korte, L., Kral, K., Kumar, J., Larson, A. J., Li, Y., Li, X., Liu, S., Lum, S. K. Y., Lutz, J. A., Ma, K., Maddalena, D. M., Makana, J.-R., Malhi, Y., Marthens, T., Serudin, R. M., McMahon, S. M., McShea, W. J., Memiaghe, H. R., Mi, X., Mizuno, T., Morecroft, M., Myers, J. A., Novotny, V., Oliveira, A. A. d., Ong, P. S., Orwig, D. A.,

- Ostertag, R., Ouden, J. d., Parker, G. G., Phillips, R. P., Sack, L., Sainge, M. N., Sang, W., Sri-ngernyuang, K., Sukumar, R., Sun, I.-F., Sungpalee, W., Suresh, H. S., Tan, S., Thomas, S. C., Thomas, D. W., Thompson, J., Turner, B. L., Uriarte, M., Valencia, R., Vallejo, M. I., Vicentini, A., Vrška, T., Wang, X., Wang, X., Weiblen, G., Wolf, A., Xu, H., Yap, S., and Zimmerman, J. (2015a). CTFS-ForestGEO: a worldwide network monitoring forests in an era of global change. *Global Change Biology*, 21(2):528–549.
- Anderson-Teixeira, K. J., McGarvey, J. C., Muller-Landau, H. C., Park, J. Y., Gonzalez-Akre, E. B., Herrmann, V., Bennett, A. C., So, C. V., Bourg, N. A., Thompson, J. R., McMahon, S. M., and McShea, W. J. (2015b). Size-related scaling of tree form and function in a mixed-age forest. *Functional Ecology*, 29(12):1587–1602.
- Bartlett, M. K., Klein, T., Jansen, S., Choat, B., and Sack, L. (2016a). The correlations and sequence of plant stomatal, hydraulic, and wilting responses to drought. *Proceedings of the National Academy of Sciences*, 113(46):13098–13103.
- Bartlett, M. K., Scoffoni, C., Ardy, R., Zhang, Y., Sun, S., Cao, K., and Sack, L. (2012). Rapid determination of comparative drought tolerance traits: using an osmometer to predict turgor loss point. *Methods in Ecology and Evolution*, 3(5):880–888.
- Bartlett, M. K., Zhang, Y., Yang, J., Kreidler, N., Sun, S.-W., Lin, L., Hu, Y.-H., Cao, K.-F., and Sack, L. (2016b). Drought tolerance as a driver of tropical forest assembly: resolving spatial signatures for multiple processes. *Ecology*, 97(2):503–514.
- Bates, D., Maechler, M., Bolker, B., and Walker, S. (2019). *lme4: Linear Mixed-Effects Models using 'Eigen' and S4*. R package version 1.1-21.
- Bennett, A. C., McDowell, N. G., Allen, C. D., and Anderson-Teixeira, K. J. (2015). Larger trees suffer most during drought in forests worldwide. *Nature Plants*, 1(10):15139.
- Beven, K. J. and Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sciences Bulletin*, 24(1):43–69.
- Bonan, G. B. (2008). Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science*, 320(5882):1444–1449.
- Bourg, N. A., McShea, W. J., Thompson, J. R., McGarvey, J. C., and Shen, X. (2013). Initial census, woody seedling, seed rain, and stand structure data for the SCBI SIGEO Large Forest Dynamics Plot. *Ecology*, 94(9):2111–2112.
- Bretfeld, M., Ewers, B. E., and Hall, J. S. (2018). Plant water use responses along secondary forest succession during the 2015–2016 El Niño drought in Panama. *New Phytologist*, 219(3):885–899.
- Brewer, M. J., Butler, A., and Cooksley, S. L. (2016). The relative performance of AIC, AICC and BIC in the presence of unobserved heterogeneity. *Methods in Ecology and Evolution*, 7(6):679–692.
- Brum, M., Vadeboncoeur, M. A., Ivanov, V., Asbjornsen, H., Saleska, S., Alves, L. F., Penha, D., Dias, J. D., Aragão, L. E. O. C., Barros, F., Bittencourt, P., Pereira, L., and Oliveira, R. S. (2019). Hydrological niche



segregation defines forest structure and drought tolerance strategies in a seasonal Amazon forest. *Journal of Ecology*, 107(1):318–333.

Campbell, G. S. and Norman, J. M. (1998). *An Introduction to Environmental Biophysics*, volume 2nd. Springer, New York.

Chitra-Tarak, R., Ruiz, L., Dattaraja, H. S., Kumar, M. S. M., Riotte, J., Suresh, H. S., McMahon, S. M., and Sukumar, R. (2018). The roots of the drought: Hydrology and water uptake strategies mediate forest-wide demographic response to precipitation. *Journal of Ecology*, 106(4):1495–1507.

Christoffersen, B. O., Gloor, M., Fauset, S., Fyllas, N. M., Galbraith, D. R., Baker, T. R., Kruijt, B., Rowland, L., Fisher, R. A., Binks, O. J., Sevanto, S., Xu, C., Jansen, S., Choat, B., Mencuccini, M., McDowell, N. G., and Meir, P. (2016). Linking hydraulic traits to tropical forest function in a size-structured and trait-driven model (TFS v.1-Hydro).

Clark, J. S., Iverson, L., Woodall, C. W., Allen, C. D., Bell, D. M., Bragg, D. C., D’Amato, A. W., Davis, F. W., Hersh, M. H., Ibanez, I., Jackson, S. T., Matthews, S., Pederson, N., Peters, M., Schwartz, M. W., Waring, K. M., and Zimmermann, N. E. (2016). The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology*, 22(7):2329–2352.

Condit, R. (1998). *Tropical Forest Census Plots: Methods and Results from Barro Colorado Island, Panama and a Comparison with Other Plots*. Springer Berlin Heidelberg, Berlin, Heidelberg.

Cook, B. I., Ault, T. R., and Smerdon, J. E. (2015). Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, 1(1):e1400082.

Couvreur, V., Ledder, G., Manzoni, S., Way, D. A., Muller, E. B., and Russo, S. E. (2018). Water transport through tall trees: A vertically explicit, analytical model of xylem hydraulic conductance in stems. *Plant, Cell & Environment*, 41(8):1821–1839.

Dai, A., Zhao, T., and Chen, J. (2018). Climate Change and Drought: a Precipitation and Evaporation Perspective. *Current Climate Change Reports*, 4(3):301–312.

Davis, K. T., Dobrowski, S. Z., Holden, Z. A., Higuera, P. E., and Abatzoglou, J. T. (2019). Microclimatic buffering in forests of the future: the role of local water balance. *Ecography*, 42(1):1–11.

de Mendiburu, F. (2020). *agricolae: Statistical Procedures for Agricultural Research*. R package version 1.3-3.

DeSoto, L., Cailleret, M., Sterck, F., Jansen, S., Kramer, K., Robert, E. M. R., Aakala, T., Amoroso, M. M., Bigler, C., Camarero, J. J., Čufar, K., Gea-Izquierdo, G., Gillner, S., Haavik, L. J., Hereş, A.-M., Kane, J. M., Kharuk, V. I., Kitzberger, T., Klein, T., Levanič, T., Linares, J. C., Mäkinen, H., Oberhuber, W., Papadopoulos, A., Rohner, B., Sangüesa-Barreda, G., Stojanovic, D. B., Suárez, M. L., Villalba, R., and Martínez-Vilalta, J. (2020). Low growth resilience to drought is related to future mortality risk in trees. *Nature Communications*, 11(1):545.

Detto, M., Muller-Landau, H. C., Mascaro, J., and Asner, G. P. (2013). Hydrological Networks and Associated Topographic Variation as Templates for the Spatial Organization of Tropical Forest Vegetation. *PLOS ONE*, 8(10):e76296.

Druckenbrod, D. L., Martin-Benito, D., Orwig, D. A., Pederson, N., Poulter, B., Renwick, K. M., and

- Shugart, H. H. (2019). Redefining temperate forest responses to climate and disturbance in the eastern United States: New insights at the mesoscale. *Global Ecology and Biogeography*, 28(5):557–575.
- Elliott, K. J., Miniati, C. F., Pederson, N., and Laseter, S. H. (2015). Forest tree growth response to hydroclimate variability in the southern Appalachians. *Global Change Biology*, 21(12):4627–4641.
- Enquist, B. J. and Niklas, K. J. (2002). Global Allocation Rules for Patterns of Biomass Partitioning in Seed Plants. *Science*, 295(5559):1517–1520.
- Farrell, C., Szota, C., and Arndt, S. K. (2017). Does the turgor loss point characterize drought response in dryland plants? *Plant, Cell & Environment*, 40(8):1500–1511.
- Fletcher, L. R., Cui, H., Callahan, H., Scoffoni, C., John, G. P., Bartlett, M. K., Burge, D. O., and Sack, L. (2018). Evolution of leaf structure and drought tolerance in species of Californian Ceanothus. *American Journal of Botany*, 105(10):1672–1687.
- Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N. (2006). Climate–Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison. *Journal of Climate*, 19(14):3337–3353.
- Friedrichs, D. A., Trouet, V., Büntgen, U., Frank, D. C., Esper, J., Neuwirth, B., and Löffler, J. (2009). Species-specific climate sensitivity of tree growth in Central-West Germany. *Trees*, 23(4):729.
- Gessler, A., Bottero, A., Marshall, J., and Arend, M. (2020). The way back: recovery of trees from drought and its implication for acclimation. *New Phytologist*.
- Gillerot, L., Forrester, D. I., Bottero, A., Rigling, A., and Lévesque, M. (2020). Tree Neighbourhood Diversity Has Negligible Effects on Drought Resilience of European Beech, Silver Fir and Norway Spruce. *Ecosystems*.
- Gonzalez-Akre, E., Anderson-Teixeira, K., McGregor, I., Herrmann, V., and RHelcoski (2019). SCBI-ForestGEO/SCBI-ForestGEO-Data: first official release.
- Gonzalez-Akre, E., Meakem, V., Eng, C.-Y., Tepley, A. J., Bourg, N. A., McShea, W., Davies, S. J., and Anderson-Teixeira, K. (2016). Patterns of tree mortality in a temperate deciduous forest derived from a large forest dynamics plot. *Ecosphere*, 7(12):e01595.
- Greenwood, S., Ruiz-Benito, P., Martínez-Vilalta, J., Lloret, F., Kitzberger, T., Allen, C. D., Fensham, R., Laughlin, D. C., Kattge, J., Bönsch, G., Kraft, N. J. B., and Jump, A. S. (2017). Tree mortality across biomes is promoted by drought intensity, lower wood density and higher specific leaf area. *Ecology Letters*, 20(4):539–553.
- Guerfel, M., Baccouri, O., Boujnah, D., Chaïbi, W., and Zarrouk, M. (2009). Impacts of water stress on gas exchange, water relations, chlorophyll content and leaf structure in the two main Tunisian olive (*Olea europaea* L.) cultivars. *Scientia Horticulturae*, 119(3):257–263.
- Hacket-Pain, A. J., Cavin, L., Friend, A. D., and Jump, A. S. (2016). Consistent limitation of growth by high temperature and low precipitation from range core to southern edge of European beech indicates widespread vulnerability to changing climate. *European Journal of Forest Research*, 135(5):897–909.

- Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology*, 34(3):623–642.
- Helcoski, R., Tepley, A. J., Pederson, N., McGarvey, J. C., Meakem, V., Herrmann, V., Thompson, J. R., and Anderson-Teixeira, K. J. (2019). Growing season moisture drives interannual variation in woody productivity of a temperate deciduous forest. *New Phytologist*, 0(0).
- Hoffmann, W. A., Marchin, R. M., Abit, P., and Lau, O. L. (2011). Hydraulic failure and tree dieback are associated with high wood density in a temperate forest under extreme drought. *Global Change Biology*, 17(8):2731–2742.
- Hollister, J. (2018). *elevatr: Access Elevation Data from Various APIs*. R package version 0.2.0.
- Hui, D., Wang, J., Shen, W., Le, X., Ganter, P., and Ren, H. (2014). Near Isometric Biomass Partitioning in Forest Ecosystems of China. *PLOS ONE*, 9(1):e86550. Publisher: Public Library of Science.
- Hyndman, R., Athanasopoulos, G., Bergmeir, C., Caceres, G., Chhay, L., O’Hara-Wild, M., Petropoulos, F., Razbash, S., Wang, E., and Yasmeeen, F. (2020). *forecast: Forecasting Functions for Time Series and Linear Models*. R package version 8.12.
- Intergovernmental Panel on Climate Change (2015). *Climate Change 2014: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the IPCC Fifth Assessment Report. Volume 2 Volume 2*. OCLC: 900892773.
- Jennings, S. B., Brown, N. D., and Sheil, D. (1999). Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. *Forestry: An International Journal of Forest Research*, 72(1):59–74.
- Kannenbergh, S. A., Novick, K. A., Alexander, M. R., Maxwell, J. T., Moore, D. J. P., Phillips, R. P., and Anderegg, W. R. L. (2019). Linking drought legacy effects across scales: From leaves to tree rings to ecosystems. *Global Change Biology*, 0(ja).
- Katabuchi, M. (2019). *LeafArea: Rapid Digital Image Analysis of Leaf Area*. R package version 0.1.8.
- Kennedy, D., Swenson, S., Oleson, K. W., Lawrence, D. M., Fisher, R., Costa, A. C. L. d., and Gentine, P. (2019). Implementing Plant Hydraulics in the Community Land Model, Version 5. *Journal of Advances in Modeling Earth Systems*, 11(2):485–513.
- Koike, T., Kitao, M., Maruyama, Y., Mori, S., and Lei, T. T. (2001). Leaf morphology and photosynthetic adjustments among deciduous broad-leaved trees within the vertical canopy profile. *Tree Physiology*, 21(12-13):951–958.
- Kunert, N., Aparecido, L. M. T., Wolff, S., Higuchi, N., Santos, J. d., Araujo, A. C. d., and Trumbore, S. (2017). A revised hydrological model for the Central Amazon: The importance of emergent canopy trees in the forest water budget. *Agricultural and Forest Meteorology*, 239:47–57.
- Larjavaara, M. and Muller-Landau, H. C. (2013). Measuring tree height: a quantitative comparison of two common field methods in a moist tropical forest. *Methods in Ecology and Evolution*, 4(9):793–801.
- Liu, H., Gleason, S. M., Hao, G., Hua, L., He, P., Goldstein, G., and Ye, Q. (2019). Hydraulic traits are coordinated with maximum plant height at the global scale. *Science Advances*, 5(2):eaav1332.

- Liu, Y. and Muller, R. N. (1993). Effect of Drought and Frost on Radial Growth of Overstory and Undersstory Stems in a Deciduous Forest. *The American Midland Naturalist*, 129(1):19–25.
- Lloret, F., Keeling, E. G., and Sala, A. (2011). Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests. *Oikos*, 120(12):1909–1920.
- Lunch, C., Laney, C., Mietkiewicz, N., Sokol, E., Cawley, K., and NEON (National Ecological Observatory Network) (2020). *neonUtilities: Utilities for Working with NEON Data*. R package version 1.3.5.
- Martin-Benito, D. and Pederson, N. (2015). Convergence in drought stress, but a divergence of climatic drivers across a latitudinal gradient in a temperate broadleaf forest. *Journal of Biogeography*, 42(5):925–937.
- Martin-Benito, D. and Pederson, N. (2015). Convergence in drought stress, but a divergence of climatic drivers across a latitudinal gradient in a temperate broadleaf forest. *Journal of Biogeography*, 42(5):925–937.
- Maréchaux, I., Bartlett, M. K., Sack, L., Baraloto, C., Engel, J., Joetzjer, E., and Chave, J. (2015). Drought tolerance as predicted by leaf water potential at turgor loss point varies strongly across species within an Amazonian forest. *Functional Ecology*, 29(10):1268–1277.
- Maréchaux, I., Saint-André, L., Bartlett, M. K., Sack, L., and Chave, J. (2019). Leaf drought tolerance cannot be inferred from classic leaf traits in a tropical rainforest. *Journal of Ecology*.
- Mazerolle, M. J. and portions of code contributed by Dan Linden. (2019). *AICcmodavg: Model Selection and Multimodel Inference Based on (Q)AIC(c)*. R package version 2.2-2.
- McDowell, N. G. and Allen, C. D. (2015). Darcy’s law predicts widespread forest mortality under climate warming. *Nature Climate Change*, 5(7):669–672.
- McDowell, N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., Clark, J. S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G. C., Jackson, R. B., Johnson, D. J., Kueppers, L., Lichstein, J. W., Ogle, K., Poulter, B., Pugh, T. A. M., Seidl, R., Turner, M. G., Uriarte, M., Walker, A. P., and Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science*, 368(6494).
- McDowell, N. G., Bond, B. J., Dickman, L. T., Ryan, M. G., and Whitehead, D. (2011). Relationships Between Tree Height and Carbon Isotope Discrimination. In Meinzer, F. C., Lachenbruch, B., and Dawson, T. E., editors, *Size- and Age-Related Changes in Tree Structure and Function*, Tree Physiology, pages 255–286. Springer Netherlands, Dordrecht.
- Meakem, V., Tepley, A. J., Gonzalez-Akre, E. B., Herrmann, V., Muller-Landau, H. C., Wright, S. J., Hubbell, S. P., Condit, R., and Anderson-Teixeira, K. J. (2018). Role of tree size in moist tropical forest carbon cycling and water deficit responses. *New Phytologist*, 219(3):947–958.
- Medeiros, C. D., Scoffoni, C., John, G. P., Bartlett, M. K., Inman-Narahari, F., Ostertag, R., Cordell, S., Giardina, C., and Sack, L. (2019). An extensive suite of functional traits distinguishes Hawaiian wet and dry forests and enables prediction of species vital rates. *Functional Ecology*, 33(4):712–734.
- Meinzer, F. C., Andrade, J. L., Goldstein, G., Holbrook, N. M., Cavelier, J., and Wright, S. J. (1999). Partitioning of soil water among canopy trees in a seasonally dry tropical forest. *Oecologia*, 121(3):293–301.

- Mencuccini, M. (2003). The ecological significance of long-distance water transport: short-term regulation, long-term acclimation and the hydraulic costs of stature across plant life forms. *Plant, Cell & Environment*, 26(1):163–182.
- Metcalfe, P., Beven, K., and Freer, J. (2018). *dynatopmodel: Implementation of the Dynamic TOPMODEL Hydrological Model*. R package version 1.2.1.
- NEON (2018). National Ecological Observatory Network. 2016, 2017, 2018. Data Products: DP1.00001.001, DP1.00098.001, DP1.00002.001. Provisional data downloaded from <http://data.neonscience.org/> in May 2019. Battelle, Boulder, CO, USA.
- Olson, M., Rosell, J. A., Martínez-Pérez, C., León-Gómez, C., Fajardo, A., Isnard, S., Cervantes-Alcayde, M. A., Echeverría, A., Figueroa-Abundiz, V. A., Segovia-Rivas, A., Trueba, S., and Vázquez-Segovia, K. (2020). Xylem vessel-diameter-shoot-length scaling: ecological significance of porosity types and other traits. *Ecological Monographs*, n/a(n/a).
- Olson, M. E., Anfodillo, T., Rosell, J. A., Petit, G., Crivellaro, A., Isnard, S., León-Gómez, C., Alvarado-Cárdenas, L. O., and Castorena, M. (2014). Universal hydraulics of the flowering plants: vessel diameter scales with stem length across angiosperm lineages, habits and climates. *Ecology Letters*, 17(8):988–997.
- Olson, M. E., Soriano, D., Rosell, J. A., Anfodillo, T., Donoghue, M. J., Edwards, E. J., León-Gómez, C., Dawson, T., Martínez, J. J. C., Castorena, M., Echeverría, A., Espinosa, C. I., Fajardo, A., Gazol, A., Isnard, S., Lima, R. S., Marcati, C. R., and Méndez-Alonzo, R. (2018). Plant height and hydraulic vulnerability to drought and cold. *Proceedings of the National Academy of Sciences*, 115(29):7551–7556.
- Phillips, N. G., Ryan, M. G., Bond, B. J., McDowell, N. G., Hinckley, T. M., and Čermák, J. (2003). Reliance on stored water increases with tree size in three species in the Pacific Northwest. *Tree Physiology*, 23(4):237–245.
- Powell, T. L., Wheeler, J. K., Oliveira, A. A. R. d., Costa, A. C. L. d., Saleska, S. R., Meir, P., and Moorcroft, P. R. (2017). Differences in xylem and leaf hydraulic traits explain differences in drought tolerance among mature Amazon rainforest trees. *Global Change Biology*, 23(10):4280–4293.
- Pretzsch, H., Schütze, G., and Biber, P. (2018). Drought can favour the growth of small in relation to tall trees in mature stands of Norway spruce and European beech. *Forest Ecosystems*, 5(1):20.
- R Core Team (2019). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.
- Rey-Sánchez, A. C., Slot, M., Posada, J. M., and Kitajima, K. (2016). Spatial and seasonal variation in leaf temperature within the canopy of a tropical forest. *Climate Research*, 71(1):75–89.
- Rosas, T., Mencuccini, M., Barba, J., Cochard, H., Saura-Mas, S., and Martínez-Vilalta, J. (2019). Adjustments and coordination of hydraulic, leaf and stem traits along a water availability gradient. *New Phytologist*, 223(2):632–646.
- Roskilly, B., Keeling, E., Hood, S., Giuggiola, A., and Sala, A. (2019). Conflicting functional effects of xylem pit structure relate to the growth-longevity trade-off in a conifer species. *PNAS*. doi: [10.1073/pnas.1900734116](https://doi.org/10.1073/pnas.1900734116).

790 Ryan, M. G., Phillips, N., and Bond, B. J. (2006). The hydraulic limitation hypothesis revisited. *Plant, Cell*  
791 *& Environment*, 29(3):367–381.

792 Sapes, G., Roskilly, B., Dobrowski, S., Maneta, M., Anderegg, W. R. L., Martinez-Vilalta, J., and Sala, A.  
793 (2019). Plant water content integrates hydraulics and carbon depletion to predict drought-induced seedling  
794 mortality. *Tree Physiology*, 39(8):1300–1312.

795 Scharnweber, T., Heinze, L., Cruz-García, R., van der Maaten-Theunissen, M., and Wilmking, M. (2019).  
796 Confessions of solitary oaks: We grow fast but we fear the drought. *Dendrochronologia*, 55:43–49.

797 Scholz, F. G., Phillips, N. G., Bucci, S. J., Meinzer, F. C., and Goldstein, G. (2011). Hydraulic Capacitance:  
798 Biophysics and Functional Significance of Internal Water Sources in Relation to Tree Size. In Meinzer,  
799 F. C., Lachenbruch, B., and Dawson, T. E., editors, *Size- and Age-Related Changes in Tree Structure and*  
800 *Function*, Tree Physiology, pages 341–361. Springer Netherlands, Dordrecht.

801 Schöngart, J., Bräuning, A., Barbosa, A. C. M. C., Lisi, C. S., and de Oliveira, J. M. (2017).  
802 Dendroecological Studies in the Neotropics: History, Status and Future Challenges. In Amoroso, M. M.,  
803 Daniels, L. D., Baker, P. J., and Camarero, J. J., editors, *Dendroecology: Tree-Ring Analyses Applied to*  
804 *Ecological Studies*, Ecological Studies, pages 35–73. Springer International Publishing, Cham.

805 Scoffoni, C., Vuong, C., Diep, S., Cochard, H., and Sack, L. (2014). Leaf Shrinkage with Dehydration:  
806 Coordination with Hydraulic Vulnerability and Drought Tolerance. *Plant Physiology*, 164(4):1772–1788.

807 Simeone, C., Maneta, M. P., Holden, Z. A., Sapes, G., Sala, A., and Dobrowski, S. Z. (2019). Coupled  
808 ecohydrology and plant hydraulics modeling predicts ponderosa pine seedling mortality and lower treeline  
809 in the US Northern Rocky Mountains. *New Phytologist*, 221(4):1814–1830.

810 Slette, I. J., Post, A. K., Awad, M., Even, T., Punzalan, A., Williams, S., Smith, M. D., and Knapp, A. K.  
811 (2019). How ecologists define drought, and why we should do better. *Global Change Biology*, 0(0):1–8.

812 Stahl, C., Hérault, B., Rossi, V., Burban, B., Bréchet, C., and Bonal, D. (2013). Depth of soil water uptake  
813 by tropical rainforest trees during dry periods: does tree dimension matter? *Oecologia*, 173(4):1191–1201.

814 Stovall, A. E. L., Anderson-Teixeira, K. J., and Shugart, H. H. (2018a). Assessing terrestrial laser scanning  
815 for developing non-destructive biomass allometry. *Forest Ecology and Management*, 427:217–229.

816 Stovall, A. E. L., Anderson-Teixeira, K. J., and Shugart, H. H. (2018b). Terrestrial LiDAR-derived  
817 non-destructive woody biomass estimates for 10 hardwood species in Virginia. *Data in Brief*, 19:1560–1569.

818 Stovall, A. E. L., Shugart, H., and Yang, X. (2019). Tree height explains mortality risk during an intense  
819 drought. *Nature Communications*, 10(1):1–6.

820 Stovall, A. E. L., Shugart, H. H., and Yang, X. (2020). Reply to “Height-related changes in forest  
821 composition explain increasing tree mortality with height during an extreme drought”. *Nature*  
822 *Communications*, 11(1):3401.

823 Suarez, M. L., Ghermandi, L., and Kitzberger, T. (2004). Factors predisposing episodic drought-induced tree  
824 mortality in Nothofagus— site, climatic sensitivity and growth trends. *Journal of Ecology*, 92(6):954–966.

825 Sørensen, R., Zinko, U., and Seibert, J. (2006). On the calculation of the topographic wetness index:  
826 evaluation of different methods based on field observations. *Hydrology and Earth System Sciences*,  
827 10(1):101–112.

- Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., and Sheffield, J. (2014). Global warming and changes in drought. *Nature Climate Change*, 4(1):17–22.
- Trugman, A. T., Detto, M., Bartlett, M. K., Medvigy, D., Anderegg, W. R. L., Schwalm, C., Schaffer, B., and Pacala, S. W. (2018). Tree carbon allocation explains forest drought-kill and recovery patterns. *Ecology Letters*, 21(10):1552–1560.
- Wheeler, E. A., Baas, P., and Rodgers, S. (2007). Variations In Dieot Wood Anatomy: A Global Analysis Based on the Insidewood Database. *IAWA Journal*, 28(3):229–258.
- Zach, A., Schuldt, B., Brix, S., Horna, V., Culmsee, H., and Leuschner, C. (2010). Vessel diameter and xylem hydraulic conductivity increase with tree height in tropical rainforest trees in Sulawesi, Indonesia. *Flora - Morphology, Distribution, Functional Ecology of Plants*, 205(8):506–512.
- Zellweger, F., Coomes, D., Lenoir, J., Depauw, L., Maes, S. L., Wulf, M., Kirby, K. J., Brunet, J., Kopecký, M., Máliš, F., Schmidt, W., Heinrichs, S., Ouden, J. d., Jaroszewicz, B., Buyse, G., Spicher, F., Verheyen, K., and Frenne, P. D. (2019). Seasonal drivers of understorey temperature buffering in temperate deciduous forests across Europe. *Global Ecology and Biogeography*, 28(12):1774–1786.
- Zhu, S.-D., Chen, Y.-J., Ye, Q., He, P.-C., Liu, H., Li, R.-H., Fu, P.-L., Jiang, G.-F., and Cao, K.-F. (2018). Leaf turgor loss point is correlated with drought tolerance and leaf carbon economics traits. *Tree Physiology*, 38(5):658–663.
- Zuleta, D., Duque, A., Cardenas, D., Muller-Landau, H. C., and Davies, S. J. (2017). Drought-induced mortality patterns and rapid biomass recovery in a terra firme forest in the Colombian Amazon. *Ecology*, 98(10):2538–2546.